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A "SMART" MOLECULAR SIEVE OXYGEN CONCENTRATOR WITH CONTINUOUS CYCLE TIME ADJUSTMENT

George W. Miller

KRUG Life Sciences, Inc.
San Antonio Division
P.O. Box 14307
San Antonio, Texas 78214

Jerold E. Fenner

CREW SYSTEMS DIRECTORATE
Crew Technology Division
2504 Gillingham Drive, Suite 25
Brooks Air Force Base, TX 78235-5104

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JEROLD E. FENNER, 1Lt, USAF, BSC
Chief, Oxygen Systems

F. WESLEY BAUMGARDNER, Ph.D.
Chief, Systems Research Branch

JAMES P. DIXON, Colonel, USAF, BSC
Chief, Crew Technology Division

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6. AUTHOR(S)

George W. Miller
Jerold E. Fenner

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

KRUG Life Sciences, Incorporated
San Antonio Division
P. O. Box 14307
San Antonio, Texas 78214

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Armstrong Laboratory
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13. ABSTRACT *(Maximum 200 words)*

A "smart" molecular sieve oxygen concentrator (MSOC) is controlled by a set of computer algorithms. The "smart" system automatically adjusts concentrator operating parameters to accurately control product oxygen concentration while minimizing bleed air consumption. The purpose of this effort was to determine if concentrator performance could be controlled by computer algorithms which continuously adjust concentrator cycle time.

A two-bed laboratory molecular sieve oxygen concentrator was constructed and instrumented. The concentrator was operated at ground level and ambient temperature. Computer algorithms or decision process were developed which allowed the software to control concentrator cycle time. Step changes in product flow from 5 to 40 standard liters/minute were induced by a flow controller. A signal representing the product oxygen concentration was produced by a medical gas analyzer and inputted into the computer algorithms.

Using continuous cycle time adjustment over a range of 14 to 36 seconds, the "smart" concentrator maintained the produce oxygen concentration within +2.5% of a desired concentration. The smallest incremental change in cycle time was 0.5 second. The highest observed overshoot in oxygen concentration which occurred during the step changes in product flow was about 12%. Inlet air consumption was reduced by approximately 40% when compared to operation at a constant cycle time.

"Smart" MSOC techniques, such as continuous cycle time adjustment, can significantly improve our ability to control oxygen concentrator performance. An added benefit will be reduced bleed air consumption which results in increased aircraft thrust and fuel economy.

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A "SMART" MOLECULAR SIEVE OXYGEN CONCENTRATOR WITH CONTINUOUS CYCLE TIME ADJUSTMENT

INTRODUCTION

At aircraft cabin altitudes above 10,000 feet additional oxygen is required in the breathing gas to prevent the occurrence of hypoxia. Most current aircraft oxygen systems use a liquid oxygen converter as the source of this additional oxygen. However, molecular sieve oxygen concentrators are replacing liquid oxygen systems because they are cost effective, reduce sortie turnaround time, extend the range of some aircraft, and are safer to operate and maintain. Currently, the US Air Force F-15E, B-2, B-1B, and F-22 aircraft and several US Navy aircraft are equipped with molecular sieve oxygen generating systems (MSOGS). Further, molecular sieve based systems are being developed to produce oxygen for military field hospitals.

These systems operate on the principle of pressure swing adsorption or PSA. Oxygen is separated from engine bleed air by preferential adsorption of nitrogen. Molecular sieve has a greater affinity for nitrogen because the nitrogen molecule possesses a slight polarity. This polarity allows the nitrogen molecules to compete more effectively for adsorption sites within the molecular sieve. Oxygen and argon are nonpolar, and therefore, adsorb in reduced amounts. The amount of nitrogen adsorbed is directly related to the pressure within the molecular sieve canisters. At moderate pressures (25-60 psig) nitrogen readily adsorbs within the molecular sieve crystals, thereby, concentrating oxygen in the gas phase. When the canister is exposed to atmospheric pressure, the molecular sieve releases the nitrogen. Hence, by alternating or "swinging" the pressure within the molecular sieve canisters, nitrogen can be separated from engine bleed air or compressed air.

The simplest molecular sieve oxygen concentrator is comprised of two molecular sieve canisters, several valves, and an orifice (Figure 1). The adsorbent canisters are alternately cycled through steps of pressurization and blow-down or venting. During each step of operation one canister is pressurized while the opposite canister is vented. During the first step of the cycle, pressurized air enters a canister and the molecular sieve adsorbs the nitrogen from the air. This pressurized canister produces a flow of concentrated oxygen which exits as product gas. During this same period the opposite canister is vented to atmospheric pressure and then purged with a portion of the product oxygen which enters through the interconnecting orifice. This venting and purging removes the adsorbed nitrogen from the molecular sieve and prepares the molecular sieve for the next pressurization step. In the second step of the cycle the canisters reverse roles. The canister which was pressurized in step one is vented and the previously vented canister is pressurized. Repeating these pressurization and depressurization steps results in a continuous flow of oxygen at the concentrator outlet. The cycle time of an oxygen concentrator is defined as the time for one canister to complete one pressurization step and one blow-down or depressurization step. In general, these two steps are equal in duration.

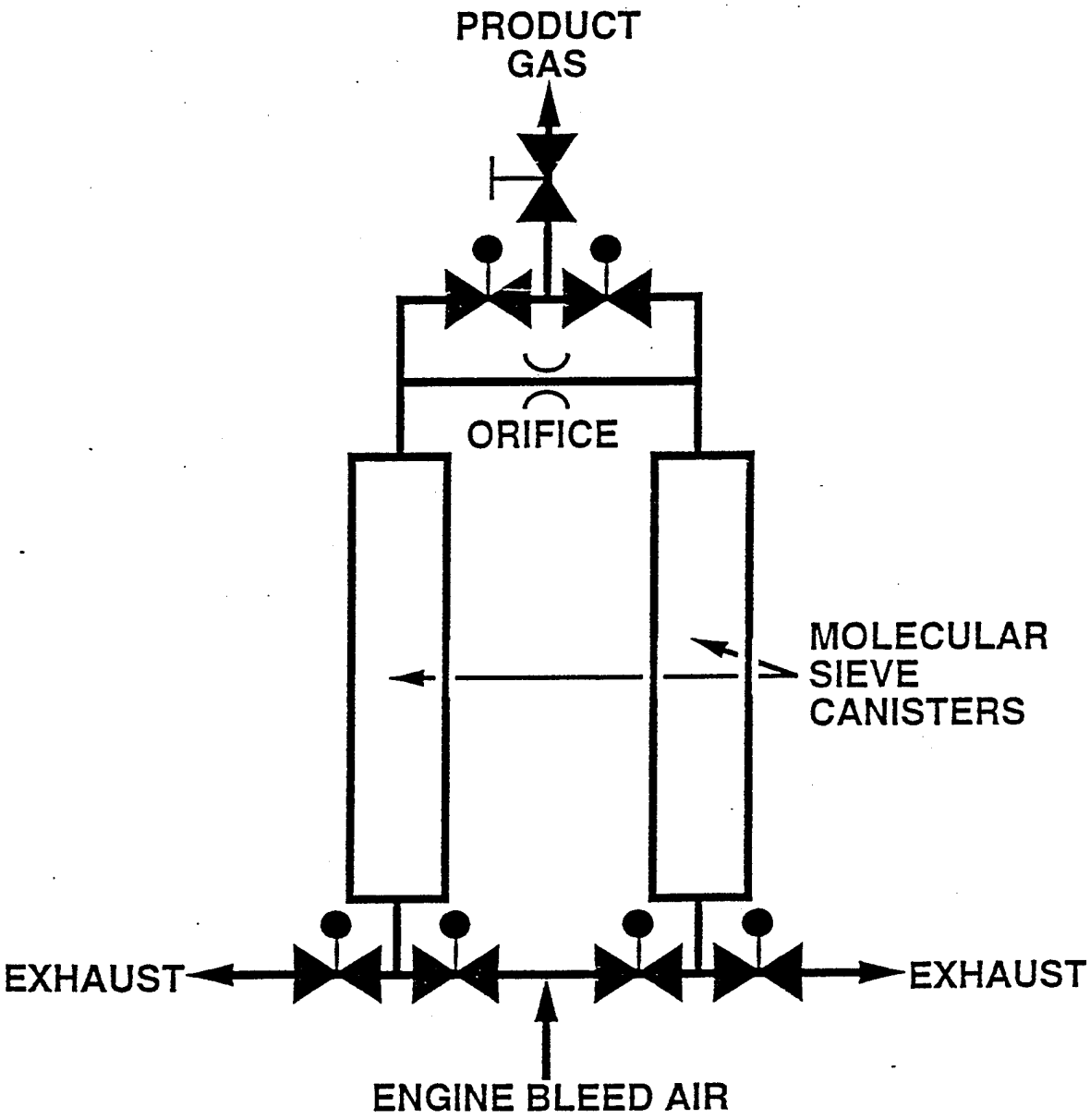

Figure 1. A Simplified Schematic of a Molecular Sieve Oxygen Concentrator.

A typical set of performance curves for a molecular sieve oxygen concentrator operated at ground level and constant cycle time is given in Figure 2. Average oxygen concentrations are shown. The outlet oxygen concentration varies with changes in inlet air pressure and product flow. Generally, at low product flows the oxygen concentrator produces a high oxygen concentration. For example, the 40 psig curve in Figure 2 has a plateau region between 10 and 20 ALPM. In this region the oxygen concentration is near 93% and very stable. This area is referred to as the "high purity plateau." At higher flows the average oxygen concentration decreases and the real time oxygen concentration wave-form fluctuates in a somewhat sinusoidal manner.

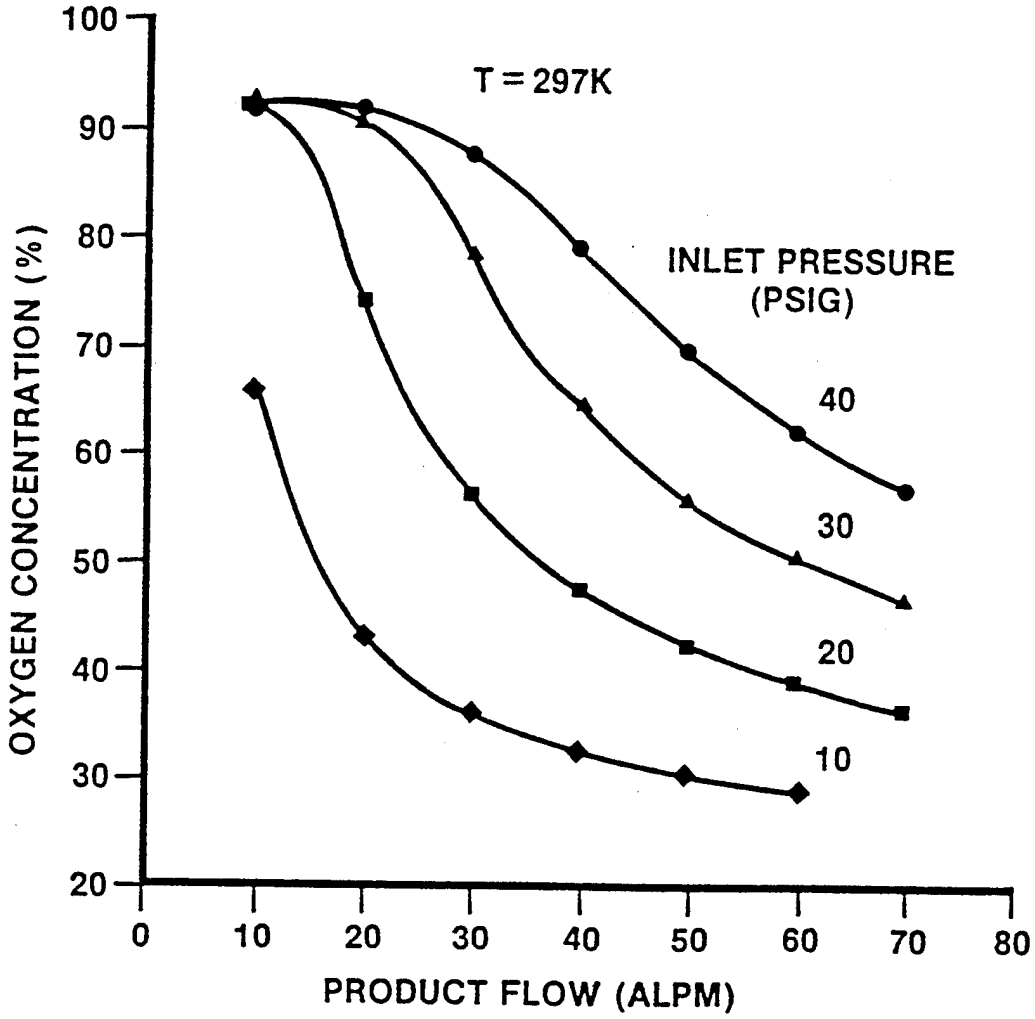

Figure 2. Typical Performance Curves for a Molecular Sieve Oxygen Concentrator.

The effect of cycle time on the product oxygen concentration is also significant. Longer cycle times generally reduce the product oxygen concentration by allowing the nitrogen wave-front to penetrate deeper into molecular sieve. Hence, a greater amount of nitrogen exits the canister with the product gas. Shorter cycle times increase the oxygen concentration but also significantly increase the air consumed. Presently, most aircraft oxygen concentrators operate at a constant cycle time of about 10 seconds. This short cycle time can produce excessively high oxygen concentrations and unnecessarily waste engine bleed air. Further, continuous operation at short cycle times may lead to a higher concentrator failure rate.

Performance curves for the B-1B MSOGS are shown in Figure 3. Average oxygen concentrations are given. These data are for operation at the predicted nominal operating conditions. The solid lines represent current system performance with OXYSIV-5 molecular sieve. The broken lines give system performance with the original MG3 molecular sieve. (Recently, the B-1B MSOGS converted to OXYSIV-5 molecular sieve.) The concentrator operates at a constant cycle time of about 9 seconds. The system was designed to produce oxygen concentrations above a minimum oxygen specification.

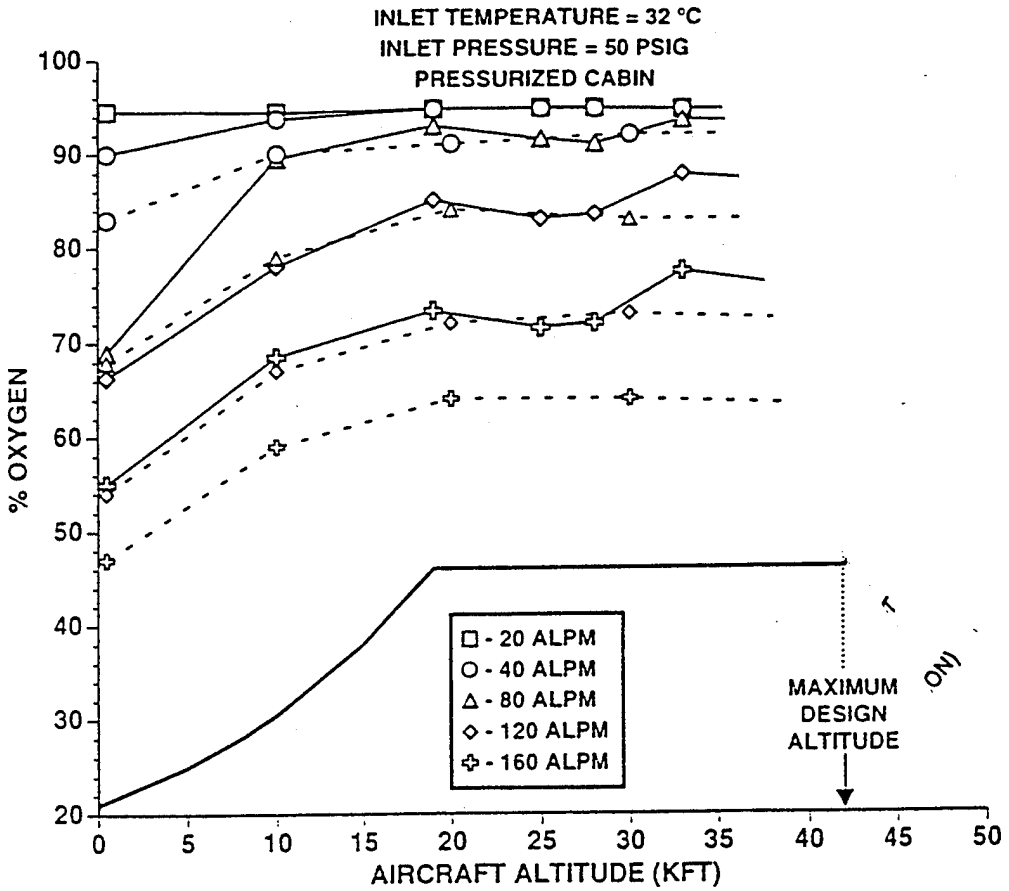

Figure 3. Performance Data for the B-1B MSOGS During Simulated Pressurized Flight at Nominal Aircraft Operating Conditions. [- - -, Data from the Original Man-Rating Report (USAFSAM-TR-87-4, August 1989)(System Contained MG3 Molecular Sieve); ___, Data with OXYSIV-5 Molecular Sieve].[2]

The B-1B system can produce oxygen concentrations which are higher than desired. The B-1B cabin altitude is maintained at 8,000 feet while the aircraft is flying at higher altitudes. The desired highest oxygen concentration in the inspired gas from ground level to 15,000 feet cabin altitude, as given in the ASCC standard, is 60%.[1] (Oxygen concentrations up to 70% have been permitted.) If the four primary crew members of the B-1B were resting (a breathing rate of approximately 10 ALPM each), then the combined demand on the MSOGS would be 40 ALPM. Under these conditions the oxygen concentration produced would be between 90% and 93% (OXYSIV-5 data at 40 ALPM in Figure 3). These higher oxygen concentrations have resulted in cases of delayed otitic barotrauma.[2] This condition produces severe ear aches after long duration missions. Because the B-1B MSOGS does not have a method for controlling the composition of the product gas, excessively high oxygen concentrations are produced.

Several methods for controlling the oxygen concentration produced by molecular sieve oxygen concentrators have been applied with varying degrees of success. These methods were introduced when oxygen concentrators had to meet both minimum and maximum oxygen concentration specifications. Three types of control methods applied were: constant cycle time operation with product gas venting; two speed cycle operation; and constant cycle time operation with product gas dilution. Constant cycle time operation with product gas venting lowers the oxygen concentration by increasing the product flow. The additional product flow is vented into the cabin. This method wastes product gas and bleed air. Two speed cycle operation involves switching the cycle time of the concentrator between two discrete speeds, one fast and one slow. At low altitudes the concentrator switches to slow speed operation and at a preset higher cabin altitude the concentrator automatically switches to fast speed operation. With two discrete speeds the concentrator typically has difficulty maintaining the oxygen concentration below the maximum specification. Also, the oxygen concentration can fluctuate significantly. Constant cycle time operation with product gas dilution can meet the minimum and maximum oxygen specifications, however, the concentrator must operate continuously at a fast cycle speed. A continuous fast cycle speed unnecessarily wastes bleed air. Also, the air taken from the cabin to dilute the product gas may introduce chemical contamination into the breathing gas. Hence, each of these methods has disadvantages.

In Figure 4 the performance curves and average oxygen concentrations for a prototype F-16 oxygen concentrator are shown.[3] The concentrator was operated at a constant cycle time of about 10 seconds. At both a moderate product flow rate (20 ALPM) and the maximum product flow rate of 50 ALPM the oxygen concentrations produced were above the desired maximum oxygen concentration. The maximum oxygen concentration specification was imposed to prevent acceleration atelectasis. To meet the oxygen concentration specifications a composition controller was added which vented additional product gas into the cabin (i.e. constant cycle time operation with product gas venting.)

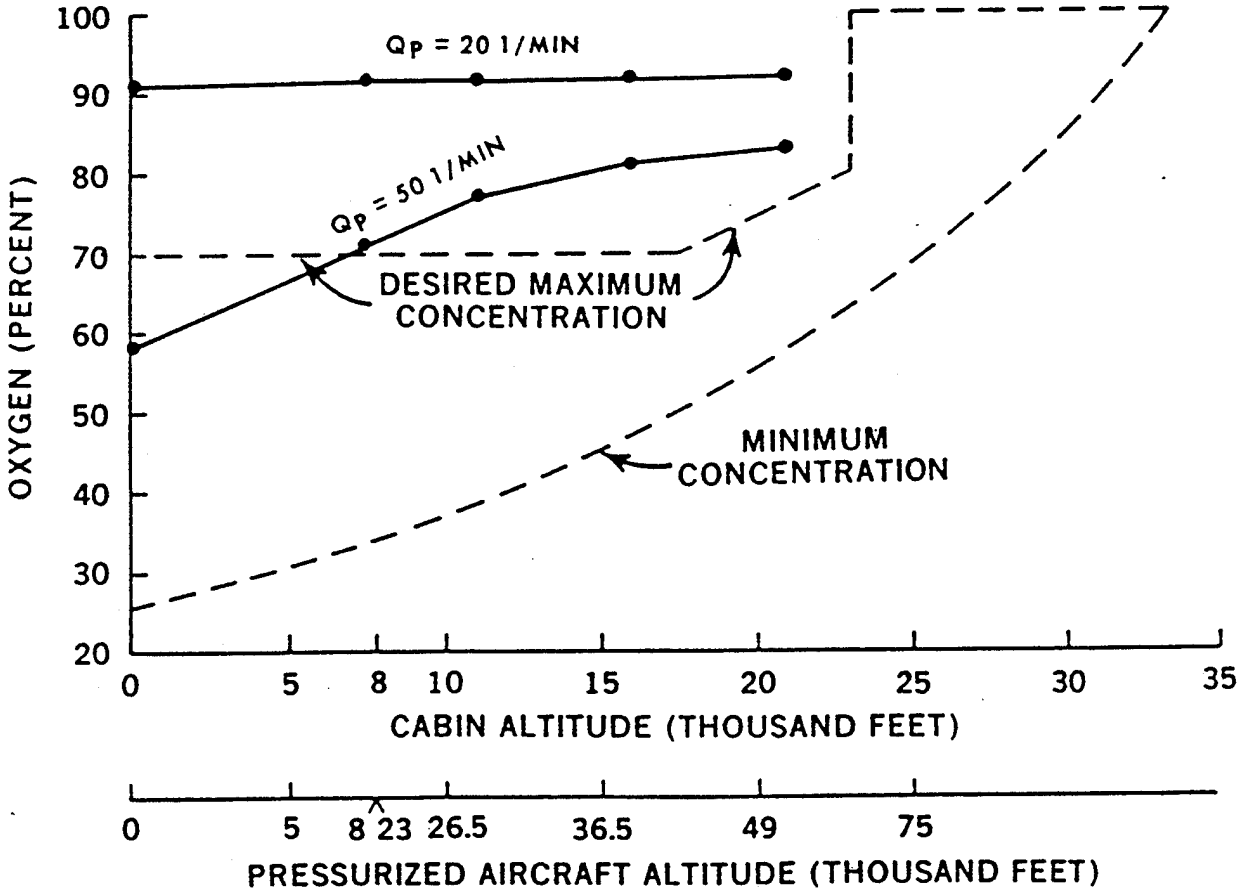

Figure 4. Performance of a Prototype F-16 Oxygen Concentrator Operated at Constant Cycle Time.[4] (Q_p is Product Flow)

In Figure 5 performance curves for the Oxygen Generation and Distribution System (OGADS) are shown.[4] This concentrator used two discrete cycle times for composition control. In general, the technique was unsuccessful because the oxygen concentrations produced were generally outside the control limits. The composition controller switched to slow cycle operation at lower altitudes and fast cycle operation at a preset higher altitude. However, this technique produced higher than desired oxygen concentrations. For example, if two crew members were breathing at an average breathing rate (15 ALPM each) and the cabin altitude remained between 8,000 to 10,000 feet, the oxygen concentrations produced would be in the range of about 85% to 93% (30 ALPM curve in Figure 5). Under these conditions the crew could experience delayed otitic barotrauma.

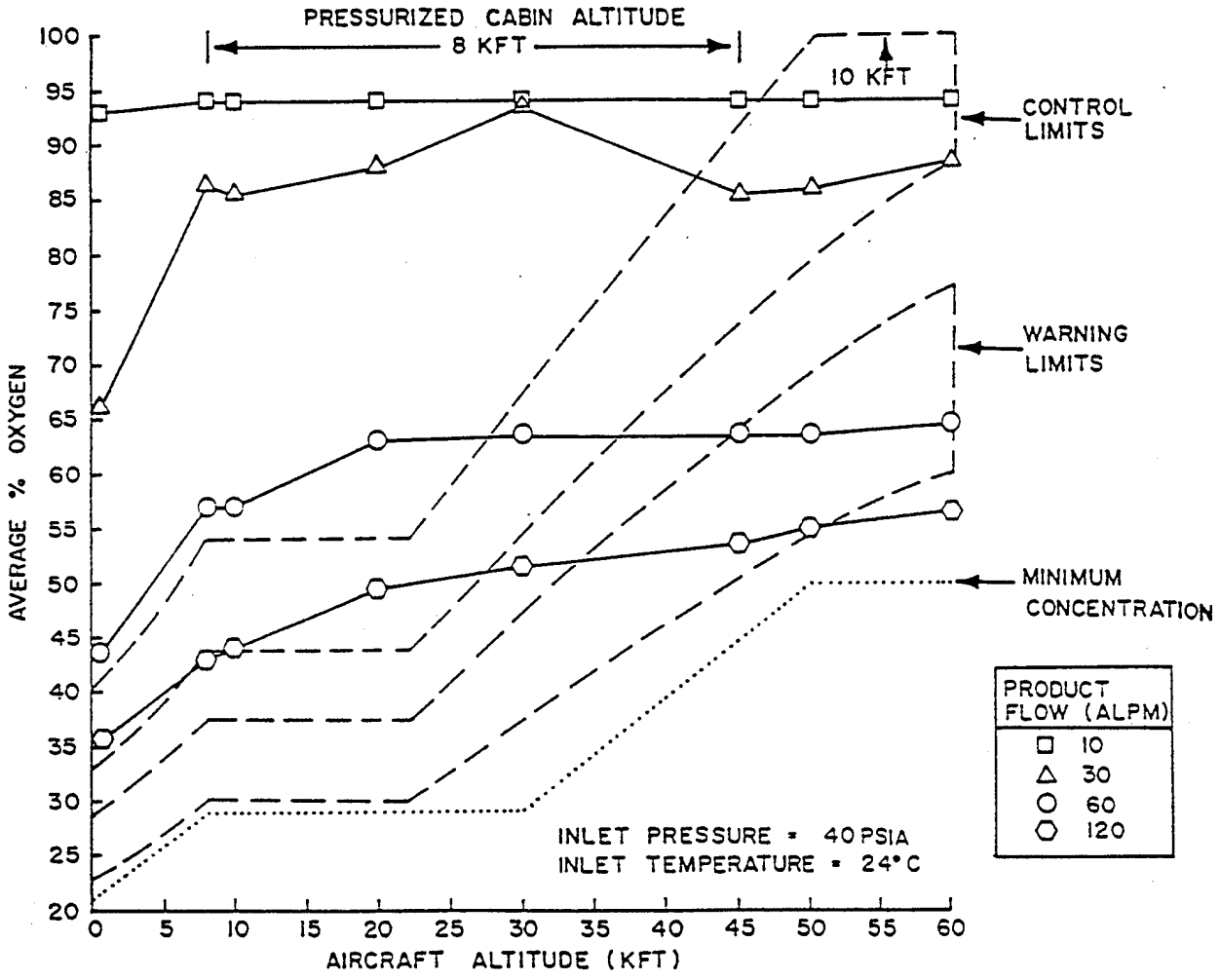

Figure 5. Performance of the Oxygen Generation and Distribution System (OGADS) with a Two Speed Composition Controller.[5]

In another case involving two speed operation, the Tactical Life Support System produced average oxygen concentrations which generally met the minimum and maximum oxygen specifications.[5] However, the swing in the oxygen concentration was significant. In Figure 6 real time oxygen concentrations for a product flow of 60 ALPM had a peak-to-peak variation of about 55% (oxygen concentrations between 33% and 88% were observed). Although the average oxygen concentration remained within the specifications, the real time oxygen concentrations fluctuated widely. This peak-to-peak variation in oxygen concentration appears excessive.

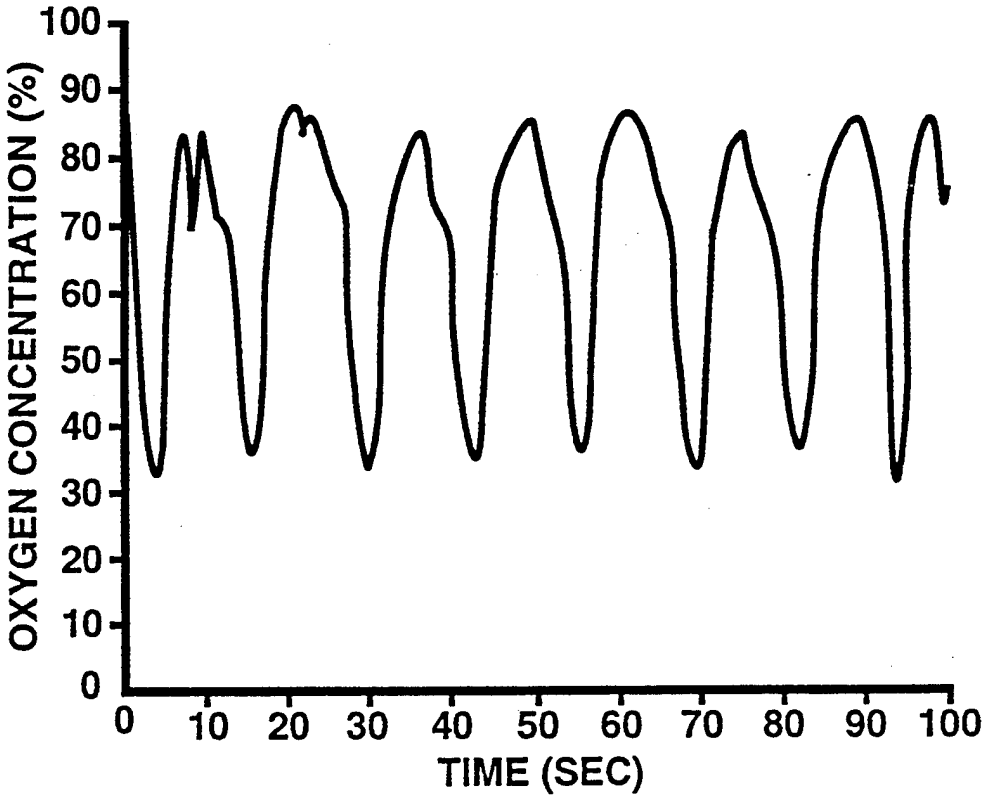

Figure 6. Real Time Oxygen Concentrations for the Tactical Life Support System (TLLS) Molecular Sieve Oxygen Concentrator During Operation at a Cabin Altitude of 8,000 feet and Aircraft Altitude of 23,000 feet with a Product Flow of 60 ALPM.[6]

The goal of this effort was to develop a "smart" oxygen concentrator by allowing computer algorithms to continuously adjust concentrator cycle time. These adjustments in cycle time regulated the product oxygen concentration. The goal was to achieve an oxygen concentration within ± 2.5% of a desired concentration. The smallest incremental change in cycle time was 0.5 second. The computer algorithms comprised a set of decision processes. The algorithms monitored the operating conditions of the concentrator, including the real time product oxygen concentration, and continuously made calculations and decisions to arrive at the most appropriate cycle time. A key objective was to achieve the desired oxygen concentration in the shortest time and at the longest cycle time. The long cycle time would minimize the bleed air consumption.

EXPERIMENTAL

A laboratory molecular sieve oxygen concentrator was constructed (Figure 7). The oxygen concentrator had two canisters filled with 3.6 Kg of 5AMG molecular sieve each. The canisters had a diameter of 4 inches and a length of 24 inches and were constructed from PVC pipe. Other components of the experimental setup were pressure transducers, a pressure regulator, air actuated valves, a flow meter, a flow controller, exhaust plenum, and a medical gas analyzer. The air actuated valves were activated by solenoid valves. The solenoid valves were controlled by the laboratory computer. Flow meter, FM1, measured the purge flow. Concentrator purge flow was varied by adjusting manual valves located upstream of FM1. Pressure transducers, P1 and P2, measured the canister inlet and outlet pressures, respectively. Pressure regulator, R1, controlled the pressure at the inlet to the flow controller, FC. The flow controller controlled the product flow from the concentrator. Step changes in product flow were achieved by changing the input control voltage to the flow controller. The Perkin Elmer MGA-1100 medical gas analyzer monitored the oxygen concentration and had an accuracy of 0.1%. The system was controlled by a data acquisition and control program operated on a PDP 11/73 computer. System testing was conducted at ground level (500 feet elevation) and room temperature.

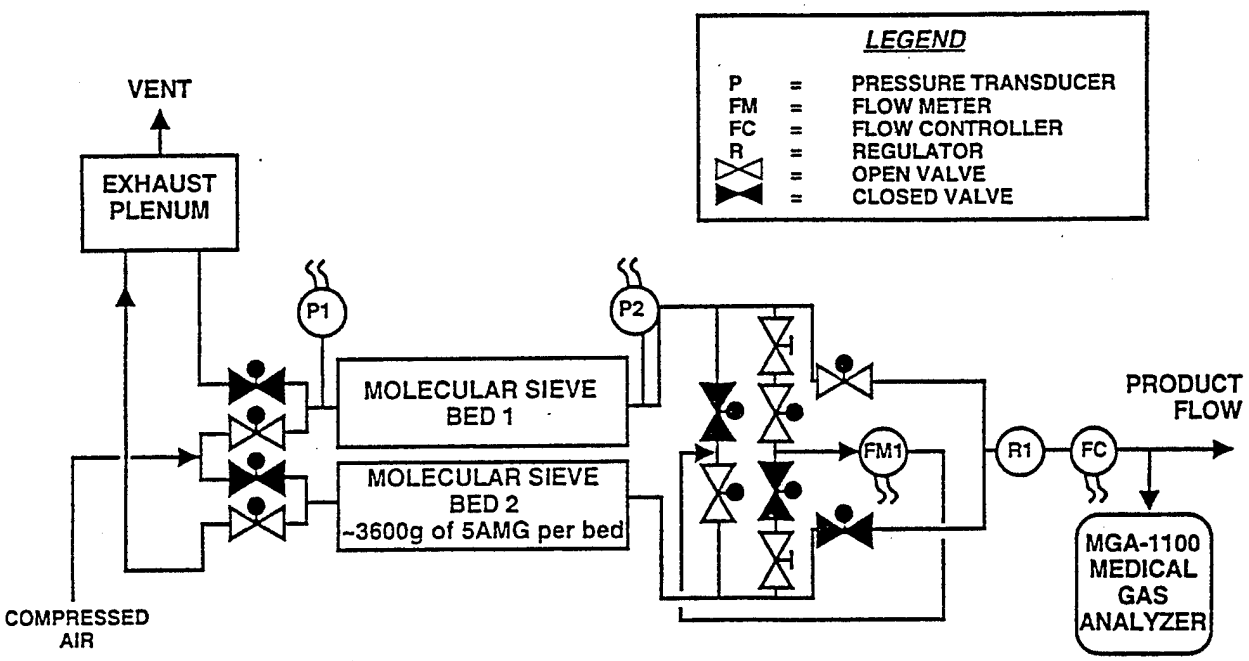

Figure 7. Simplified Schematic Diagram of the Experimental Apparatus (Valve Positions for Step 1 of the Cycle are Shown).

The optimum step time for the laboratory oxygen concentrator was determined by operating the system at a constant product flow (15 SLPM) and inlet pressure (55 psia) while the step time and purge flow were varied. The data from the optimization tests are given in Figure 8. Average oxygen concentrations are shown. The concentrator optimized at a step time of 7 seconds and a purge flow of 100 SLPM. The optimization procedure attempts to maximize the oxygen concentration and minimize the purge flow. Hence, the optimum cycle time for the concentrator was 14 seconds (cycle time = 2 · step time). This parameter was inputted into the computer algorithms.

A set of performance curves was developed for the concentrator during operation at a constant step time and purge flow (Figure 9). Average oxygen concentrations are shown. The inlet pressure and product flow were varied. Oxygen concentrations increased with increasing inlet pressure and decreasing product flow. The 55 psia curve defined the upper boundary of concentrator performance. A small improvement in performance is possible above this curve by increasing the inlet pressure, however, for this study the assumed inlet pressure was 55 psia.

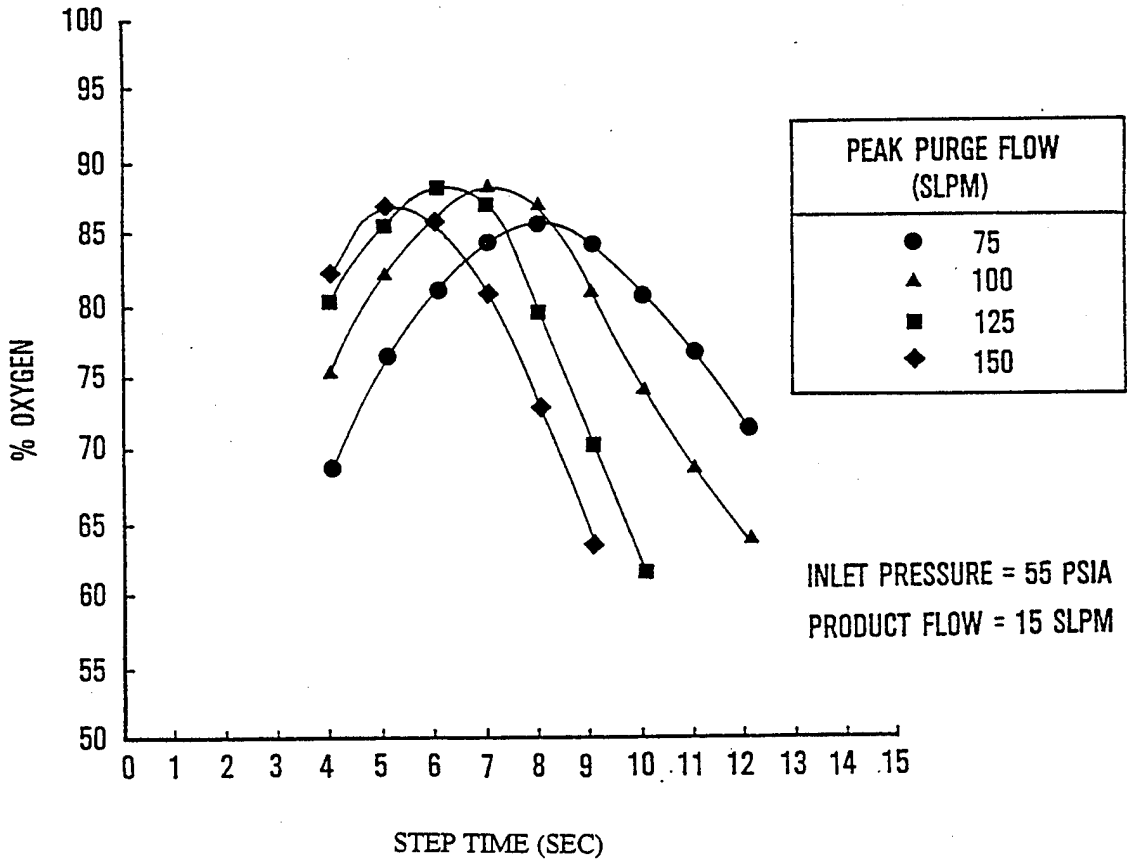

Figure 8. Performance of the Laboratory Molecular Sieve Oxygen Concentrator at Various Step Times and Purge Flows.

RESULTS

The concentrator was operated at a constant step time (7 seconds) while step changes in product flow were induced by the flow controller (Figure 10). The product flow was stepped from 5 SLPM to 40 SLPM and then returned to 5 SLPM. Step changes between a low flow rate and a high flow rate simulated the "worst case" scenario for an actual aircraft oxygen concentrator. The oxygen concentrations achieved are typical for a concentrator operating without composition control. At the low product flow the oxygen concentration is about 93%. At the high flow the average oxygen concentration drops to approximately 55%. A concentrator operated at a constant cycle time will have significant changes in oxygen concentration when the product flow is varied. The real time oxygen concentrations are given in Figure 11. The peak-to-peak wave-form variation at 40 SLPM was about 35% (the oxygen concentration varied between 35 and 70%). At 5 SLPM the oxygen concentration was stable at about 93% because the concentrator was operating in the high purity plateau region. Current aircraft oxygen concentrators operated at a constant cycle time are designed to meet the minimum oxygen

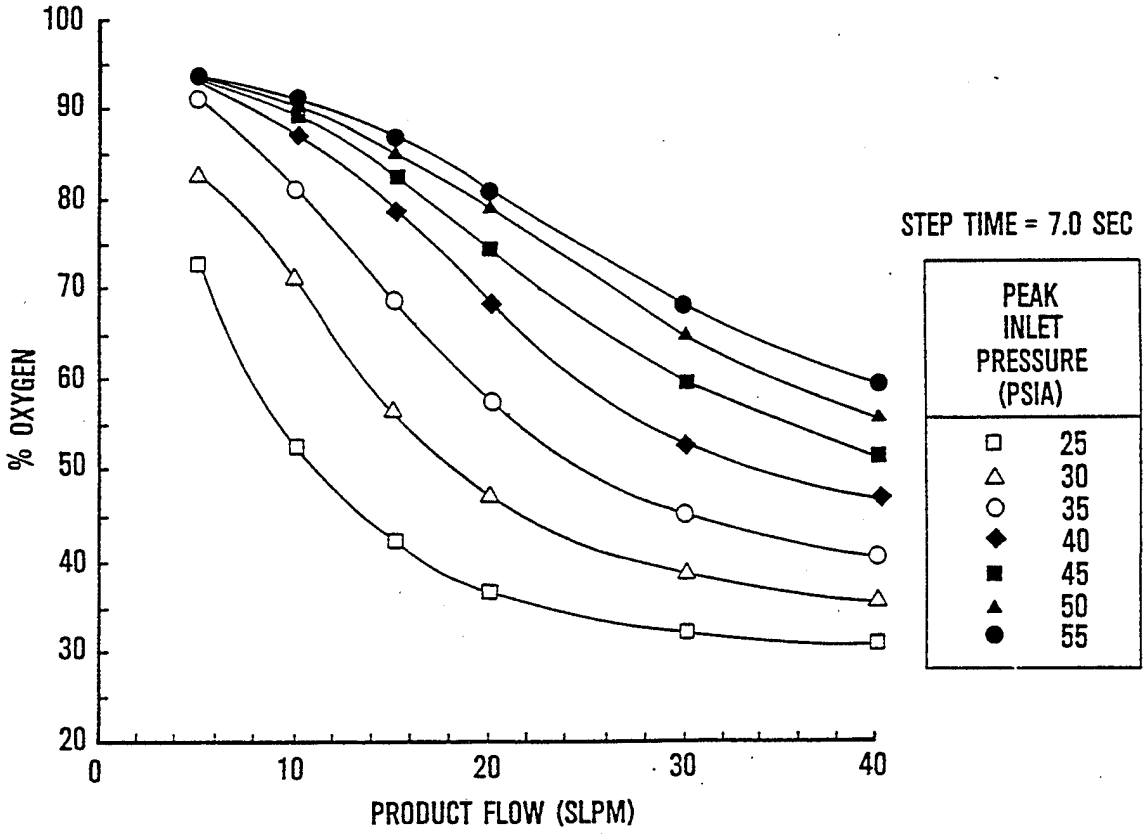

Figure 9. Performance of the Laboratory Molecular Sieve Oxygen Concentrator at Several Inlet Pressures.

specification while providing product gas at the maximum design flow rate. Therefore, during operation at lower flow rates (which is highly probable) excessive oxygen concentrations can occur.

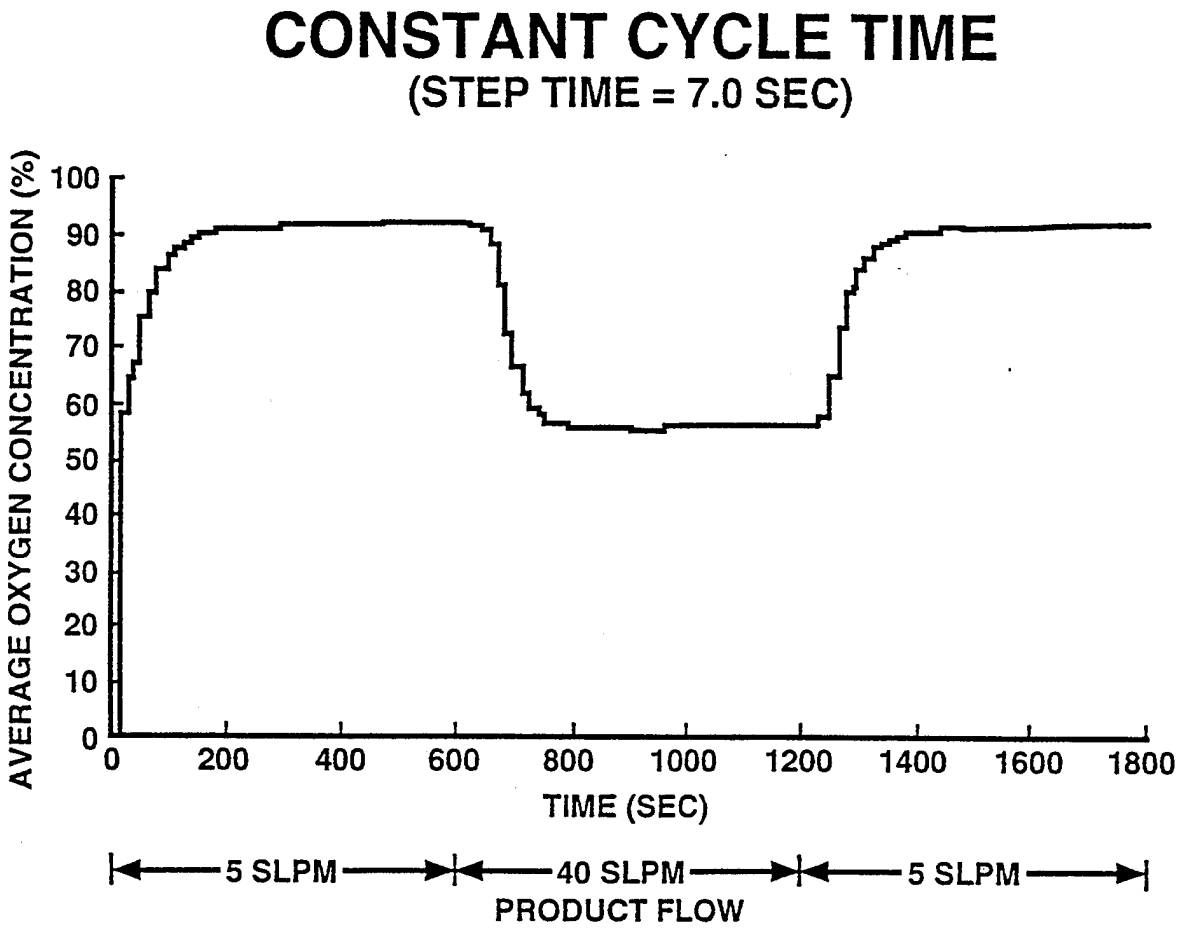

Figure 10. Performance of the Laboratory Molecular Sieve Oxygen Concentrator Operated at a Constant Cycle Time with a Step Change in Product Flow.

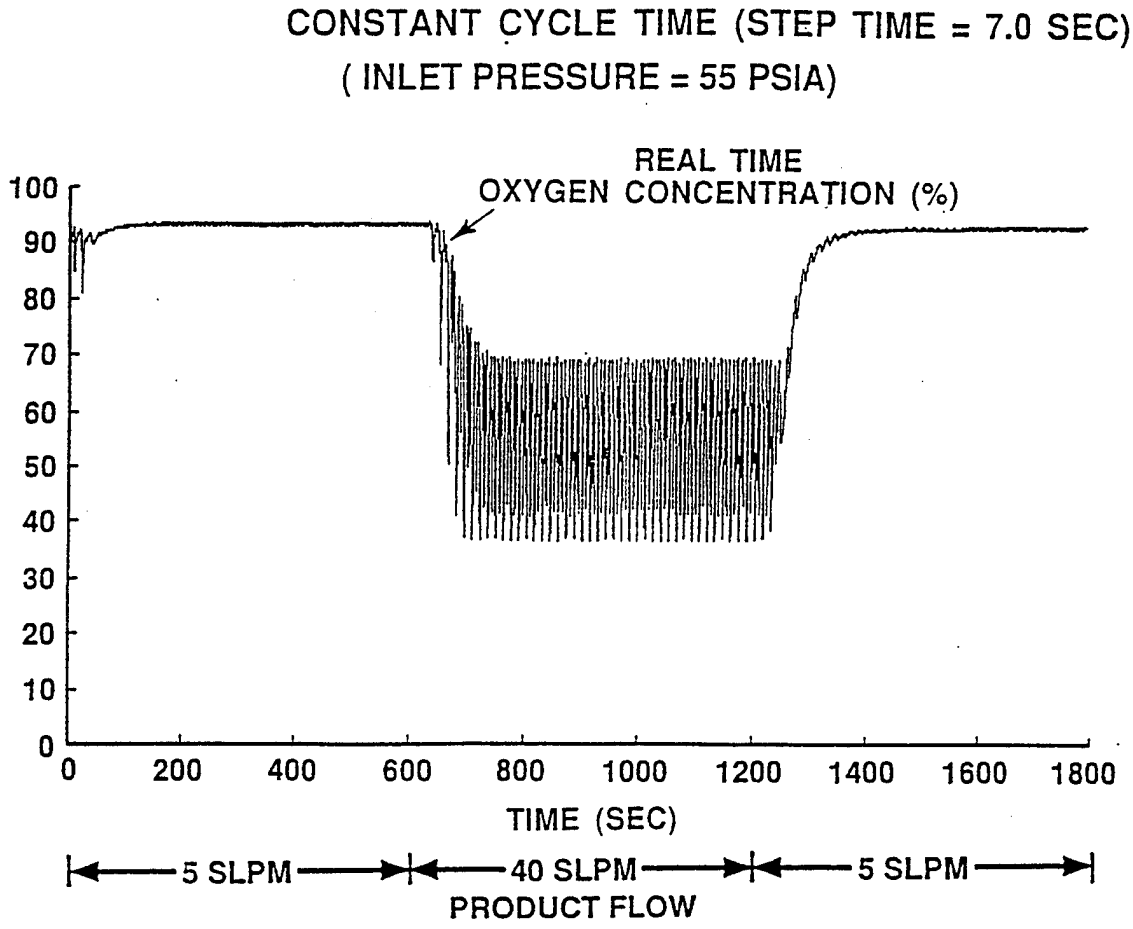

Figure 11. Real Time Oxygen Concentrations for the Laboratory Molecular Sieve Oxygen Concentrator Operated at a Constant Cycle Time with Step Changes in Product Flow.

Computer algorithms were programmed in FORTRAN for the purpose of continuously adjusting the cycle time of the concentrator. A detailed description of the algorithms used to implement this technique will not be presented here. Instead, this information will be described in a forthcoming patent application. The algorithms were added to the data acquisition and control program which ran on the PDP 11/73 computer. For this study the desired oxygen concentration was set at 38.5%. The selection of this concentration was arbitrary. A control band of 36-41% was established so that the goal would be to maintain the oxygen concentration within ±2.5% of the desired concentration. The selection of the control band range (5%) ensured that the computer algorithms were adequately challenged. A low limit was set at an oxygen concentration of 31%. Oxygen concentrations at or below the low limit would trigger the algorithms to reset the step time to 7 seconds. This step time produced maximum performance. The range between the low limit and the lower value for the control band (36%) simulated a "safety margin." In an actual aircraft system the low limit would be set at the minimum physiological oxygen concentration. The control band would be placed just above the "safety margin." During normal operation the algorithms continuously monitored the difference between the current oxygen concentration and the desired oxygen concentration. Cycle time corrections were accomplished to regulate the concentrator oxygen concentration output toward the desired control band. The testing induced large changes in product flow to evaluate the responsiveness of the algorithms.

The performance of the "smart" oxygen concentrator is given in Figure 12. Average oxygen concentration is shown. During startup the computer algorithms were programmed to set the step time to 7 seconds for approximately 30 seconds. The 30 seconds startup period allowed the oxygen concentration to ramp upward before the computer algorithms initiated control. The algorithms were programmed to vary the step time based on specific calculations and decision processes. The "smart" concentrator achieved oxygen concentrations within ±2.5% of the desired concentration (38.5%). The highest overshoot above the control band which occurred during the flow step changes was about 12%. Overshoot below the control band was not observed. The step times observed during the test run were between 7 and 18 seconds. The real time oxygen concentrations measured during the test are given in Figure 13. Peak-to-peak variation at 40 SLPM was about 18%(compared to 35% for constant cycle time operation).

A comparison of inlet air consumption for operation of the concentrator at constant cycle time and during continuous cycle time adjustment is given in Figure 14. Inlet air consumption was reduced up to 40% through the use of a "smart" oxygen concentrator methodology.

CONCLUSIONS

The "smart" system varied the step time of the oxygen concentrator to permit control of the oxygen concentration within ±2.5% of a desired value. The highest overshoot in oxygen concentration above the control band was about 12%. This overshoot is considered minimal and would have no effect on the aircrew. A 40% reduction in inlet air consumption was observed for the "smart" system with a continuously adjustable cycle time.

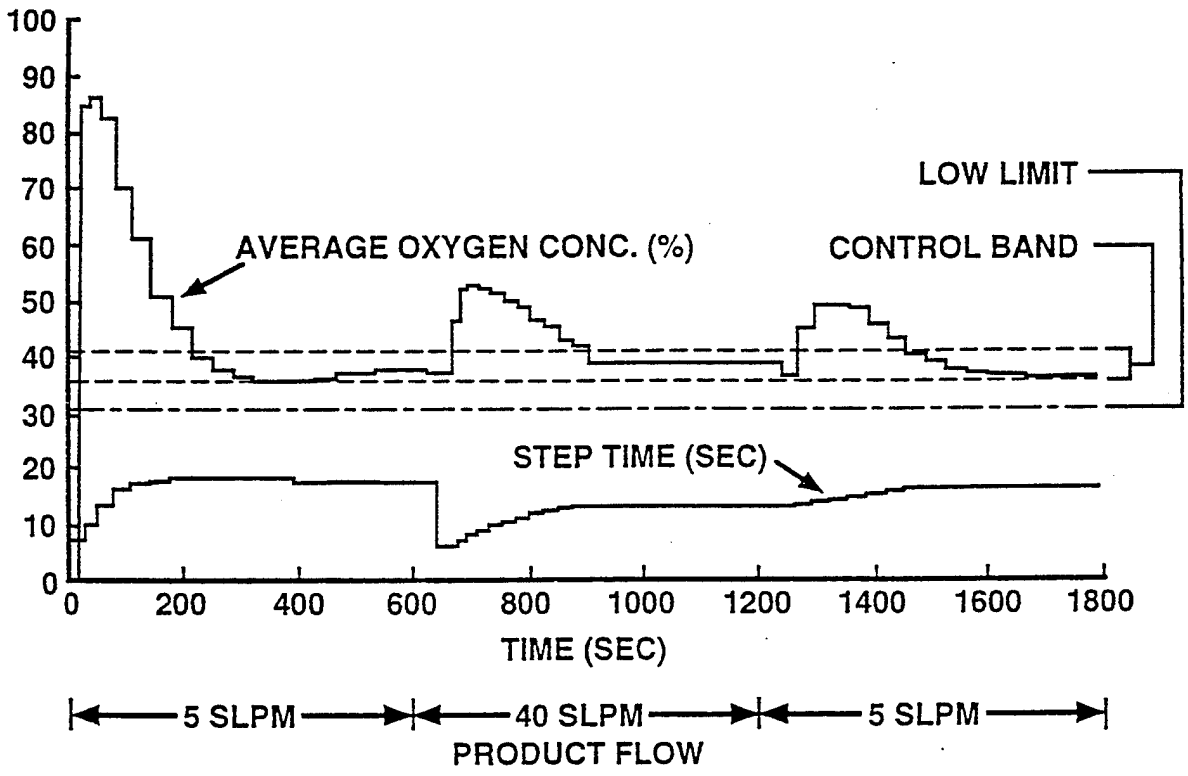

Figure 12. Performance of the "Smart" Molecular Sieve Oxygen Concentrator with Step Changes in Product Flow [Cycle Time = 2 · Step Time].

Use of "smart" molecular sieve oxygen concentrator techniques could significantly improve our ability to control the product oxygen concentration and reduce bleed air consumption. Further, these techniques would ensure that excessive oxygen concentrations do not occur.

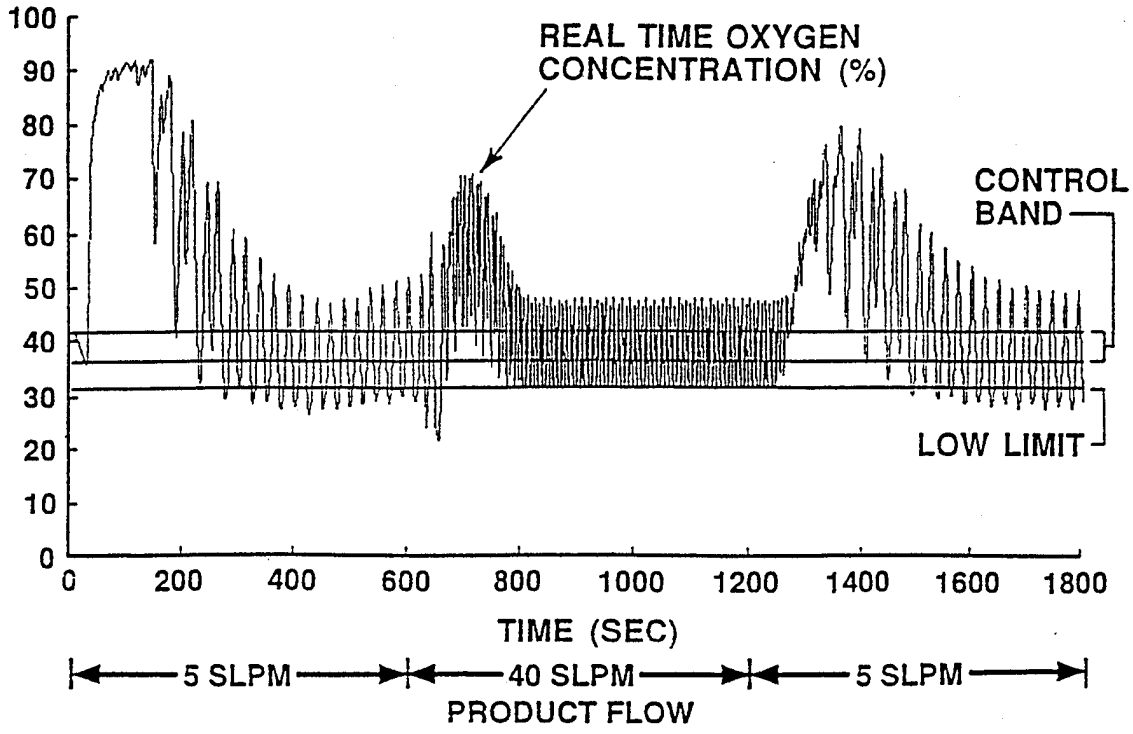

Figure 13. Real Time Oxygen Concentrations for the "Smart" Molecular Sieve Oxygen Concentrator with Step Changes in Product Flow.

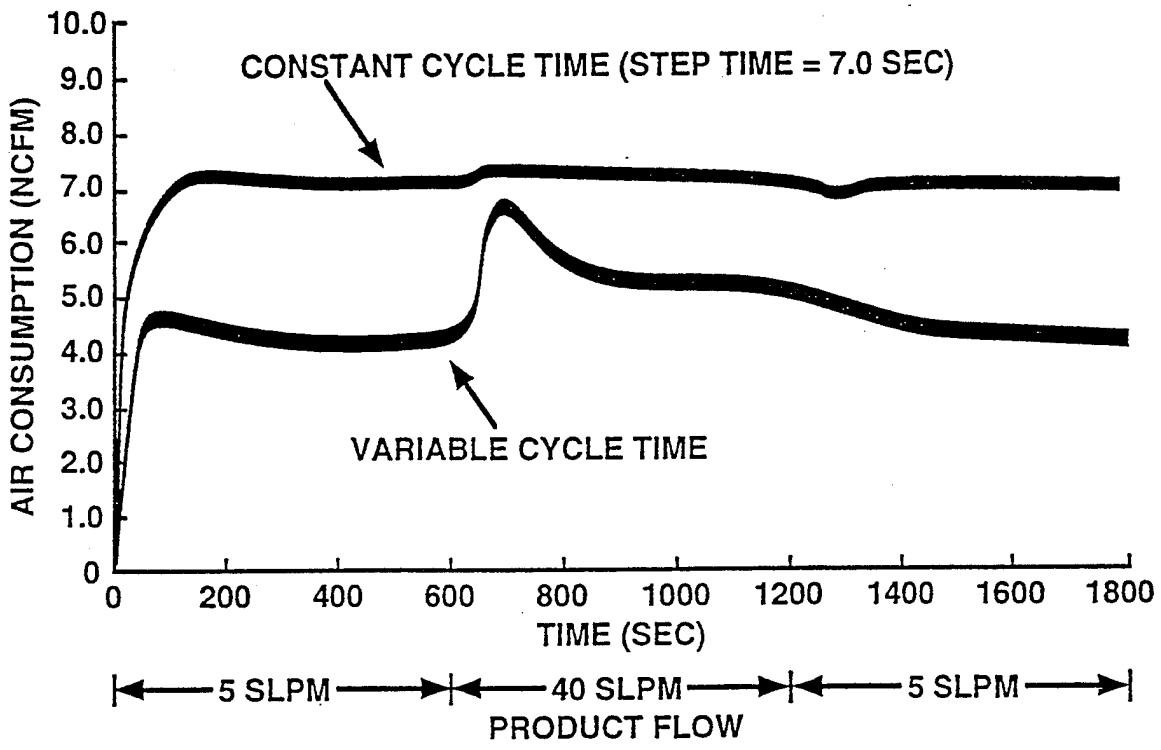

Figure 14. Inlet Air Consumption for the Laboratory Molecular Sieve Oxygen Concentrator While Operating at a Constant and Variable Cycle Time.

NOMENCLATURE

ALPM = ambient liters per minute
Kg = kilograms
NCFM = normal cubic feet per minute (ref. to 1 atm and 70°F)
psia = pounds per square inch absolute
psig = pounds per square inch gauge
SLPM = standard liters per minute (ref. to 1 atm and 0°C)

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